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Abstract. This paper presents the design and experimental evaluation of haptic rendering techniques for navigating using localized vibrotactile stimuli provided by a custom multi-actuator haptic handle. We present two haptic rendering schemes which are then used in combination with three navigation strategies to guide users along a path. We evaluate these techniques in a user study where 18 participants walk in a 8×8 m room, following haptic cues displayed by the handle. Results show that participants are able to navigate along the path successfully, with success rates ranging from 80% to 100% across conditions.

Keywords: Navigation · Handle · Multi-actuator · Vibration

1 Introduction

Safe and efficient navigation in complex or unfamiliar environments poses a daily challenge for many individuals. Nowadays, smartphone applications serve as the predominant mean for wayfinding, using GPS to display location data on screens. However, these solutions demand visual or auditory attention and may not suit individuals with visual impairments or those using mobility aids. In addressing these limitations, haptic feedback has emerged as a promising method for effectively delivering navigational cues [3,11], catering to users both with and without disabilities. Some implementations integrate haptic cues into existing assistive devices [24], while others exist as standalone systems [23]. Importantly, utilizing haptic cues avoids overloading the auditory or visual sensory channels, allowing them to be used for alternate tasks or, in some cases, for users with diminished sensory capabilities [18,19]. One of the challenges of using haptic feedback for navigation is finding a rendering scheme able to provide necessary information while staying easily understandable. Localized sensations appear to be a good fit for providing rich directional information, but they need to be coupled with an intuitive and informative navigation paradigm.

In this paper, we evaluate a set of haptic rendering techniques for navigation, combining three navigation strategies and two rendering schemes using the same custom multi-actuator haptic handle, which can provide localized vibrotactile stimuli at four distinct locations within the users' hand [4]. It also has the advantage of not being as cumbersome or challenging to equip as some wearable devices, which are often not suitable for users with physical disabilities. The three navigation strategies offer guidance by indicating a direction to follow, the deviation from the path, or the direction to return. The two rendering schemes offer different level of granularity of the navigation information, utilizing the localized feedback as a distinctive directional cue relative to the user orientation.

The main contributions of the paper can be outlined as follows:

- Design of haptic rendering techniques for navigation tailored for a custom multi-actuator haptic handle, combining three navigation strategies with two rendering schemes;
- User study evaluation involving 18 participants to assess their effectiveness in following predetermined paths within a 8×8 m room using the provided haptic navigation information.

2 Related Work

Today, GPS-based systems employing screens, audio guidance, or a blend of both are the predominant navigation devices aiding users in unfamiliar settings. Effective navigation requires instructions that users can quickly and easily interpret. To address this, haptic feedback has been proposed as an alternative means of guiding users. Indeed, as the haptic modality remains usually unengaged, providing haptic navigation information avoids interference with already overstimulated visual or auditory cues. Moreover, for individuals with disabilities or impairments, auditory or visual information might not be a suitable choice, in which case haptic feedback can be a more compatible option.

Different types of haptic cues have been employed to provide navigation information, such as skin stretch [5,13], temperature [16], pressure [17], kinesthetic feedback [7], with the most popular being vibrations [12,6,1,2]. Interfaces can be standalone devices [23,12,26,3] or integrated into a mobility assistance device, such as white canes [21,16,9,25] or walkers [24]. Kappers et al. [11] have recently presented a survey of hand-held haptic devices in walking applications, highlighting the popularity and effectiveness of vibrotactile solutions.

Interfaces with a single vibrotactile actuator can be used to provide simple proximity information [25] or more complex patterns, e.g., by using tactons [8] to encode the desired information. For example, PocketNavigator [20] uses different vibration patterns to communicate the angle between the user and the next waypoint, increasing the length of the vibration signal with the angle. NaviRadar [22] evaluates different combination of a radar sweep metaphor with intensity, duration, or rhythm to give a similar directional information.

Interfaces with multiple actuators often use the location of the vibration across the hand [23,16,26] or other body parts, such as the waist [10] or the arms [6,2], to encode spatial information. For example, HALO [25] links the actuation of each motor to a proximity sensor. In a similar way, haptic belts and wristbands use the location of the haptic stimuli to communicate a direction around the considered user limb [15,6]. The haptic cricket [23] uses its three actuators differently: the one at the front of the device has its intensity linked to the proximity to the target, while the two on the sides encode right and left deviation from the target, respectively. Lacôte et al. [14] employ a custom 5-actuator haptic handle, using the apparent haptic motion illusion to provide directional cues towards the target.

Overall, the effectiveness of vibrotactile feedback for navigation application has been proven in diverse scenarios, with one or multiple actuators. However, the use of multi-actuator in hand-held devices is less common, mainly due to the fact that providing multiple vibrations in a small area is usually not easy to understand and differentiate. Existing hand-held multi-actuator devices have rarely been evaluated in navigation application. For these reasons, in this paper, we aim to design a set of haptic-based navigation strategies by providing rich and intuitive vibration information on the hand. These strategies apply previous navigation techniques to our multi-actuator handle, capitalizing on localized feedback to improve navigation efficiency.

3 Design

3.1 Haptic hand-held vibrotactile interface

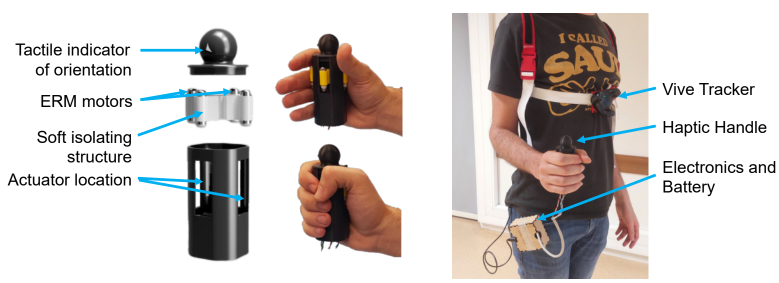

Fig. 1. Our custom haptic handle provides localized vibrotactile feedback within the user's hand thanks to four ERM actuators isolated with a soft 3D-printed structure (left). We evaluated three navigation strategies with two haptic rendering schemes, having participants follow three invisible target paths using the haptic navigation information provided by the haptic handle (right).

In our study, we utilized a custom 3D-printed hand-held haptic interface, shown in Fig. 1. It is designed to offer easily comprehensible directional haptic cues. It achieves this objective through localized multi-actuator feedback in an anthropomorphic design: the handle is topped by a spherical part, resembling a head, with a tactile indent on one side, resembling a nose. Doing this, haptic cues from the handle can be easily mapped to a direction relative to the user.

Within the handle, a soft component made of a deformable plastic (TPU) houses four 7-mm-diameter Eccentric Rotating Mass (ERM) motors, facilitating localized vibrotactile feedback. This design element was engineered to minimize the propagation of the vibrations across the handle, so as to help the user better identifying the stimuli source. This design was evaluated in more details in [4]. All electronic components were integrated with an ESP32 micro-controller and battery, that users could easily carry on their belt. Navigation commands were computed within Unity and transmitted wirelessly to the handle via ROS2.

3.2 Guidance Feedback

We designed three navigation strategies and two haptic rendering schemes for our haptic handle to guide users along reference paths. Each strategy starts by computing an angle θ, defined as the angle between the user and a navigation target on the path to follow, dependant on both the user orientation and position, as detailed in Fig. 2. θ is then mapped to a directional stimuli to be displayed by the haptic handle depending on the active rendering scheme, as described in Fig. 3.

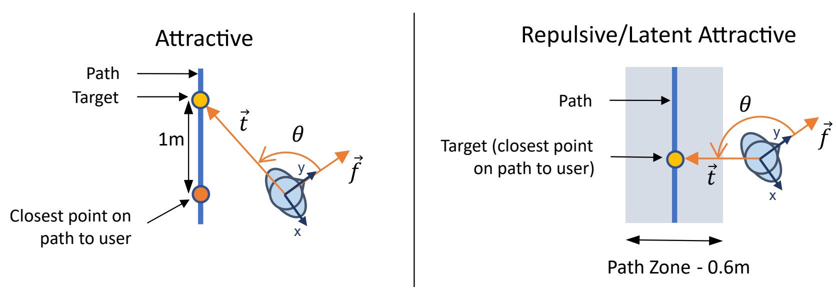

Fig. 2. Each navigation strategy (Attractive `A`, Repulsive `R`, Latent Attractive `LA`) computes a signed angle θ between the user heading direction $\overrightarrow{f}$ and a vector pointing toward a target on path $\overrightarrow{t}$. The Attractive strategy sets the target as the point on the path one meter ahead from the closest point on path to the user. The Repulsive and Latent strategies set the target to the closest point on path to the user.

The three navigation strategies provide information regarding the position of the user with respect to the target path. The Attractive strategy (`A`) provides navigation information through 0.2-s-long vibratory cues conveyed regularly every second. The Repulsive strategy (`R`) provides navigation information only when the user is more than 30 cm away from the path (i.e., out of the 60-cm-wide path zone or neighbourhood seen in Fig. 2, corresponding to the width of a side step on each side of the path), continuously conveying vibratory cues opposite to the desired motion direction. The Latent Attractive strategy (`LA`) also provides navigation information only when the user is more than 30 cm away

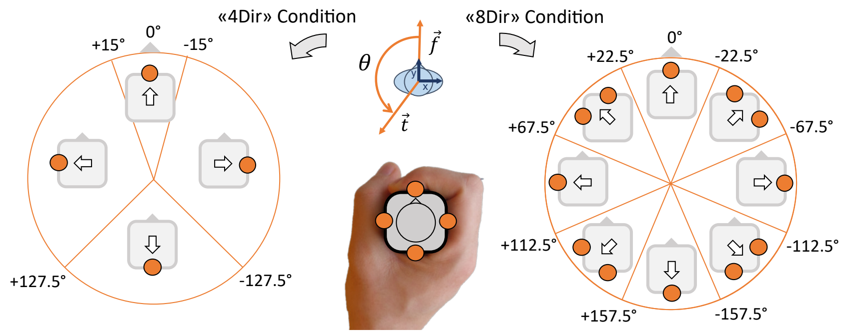

Fig. 3. Each navigation strategy can map θ into vibratory stimuli with two rendering schemes, using four (`4Dir`) or eight (`8Dir`) directions. In `4Dir`, θ is mapped into the four directions left, right, front, back, using one motor at a time; `8Dir` considers four additional directions, front-left, front-right, back-left, back-right, which simultaneously use two actuators. The location and interpretation of each stimulus are linked, e.g., the "left" stimulus is provided on the left side of the handle. Depending on the strategy used to guide the user, these stimuli are played as 0.2-s-burst every second (`A`) or continuously (`R`, `LA`).

from the path, but it continuously convey vibratory cues *towards* the desired motion direction.

The two rendering schemes provide the directional information with different levels of granularity: `4Dir` provides four directional cues while `8Dir` provides eight, as described in Fig. 3.

Representative examples of the considered combination of strategies and rendering schemes are shown in Fig. 4.

4 User Study

We recruited 18 participants (14M, 4F, aged 20-47: mean = 27.28, SD = 6.25) to take part in the study, all of whom gave their written informed consent. The study has been approved by Inria's ethics committee (COERLE, No. 2023-49). Before the start of the experiment, participants were introduced to the haptic handle and familiarized with the different haptic cues.

4.1 Experimental Setup

We conducted the experiment in a 8×8 m room (see Fig. 1). A Vive tracking system tracked the user pose. Participants wore a harness on which the Vive tracker was positioned and held the handle in their dominant hand, with the control box attached to their belt. A noise-cancelling headset was used to hide potential audio cues from the vibrations in the handle. We considered three target paths, shown in Fig. 5, which were not visible to the participants. These

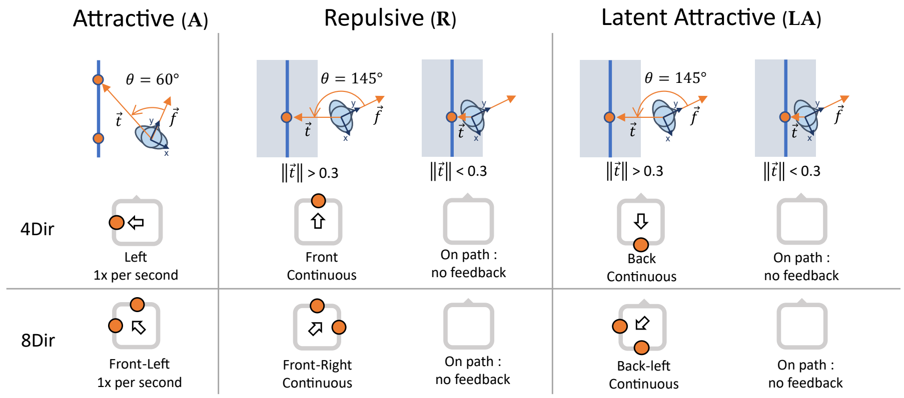

Fig. 4. Navigation strategies (Attractive `A`, Repulsive `R`, Latent Attractive `LA`) are combined with the two rendering schemes (`4Dir`, `8Dir`). The orange circles (bottom) represent the actuators which are activated on the handle, depending on the position and orientation of the user relative to the path (top).

paths were designed to have similar lengths ($13.5 \pm 1m$), each with a different combination of angles between path segments (90° for `P1`, 45° for `P1` and both 90° and 45° for `P1`), which could highlights differences between `4Dir` and `8Dir` rendering schemes. Two possible starting points on opposite sides of the room were used during the experiment to minimize learning effects (i.e., the target path could be rotated 180 degrees around the center of the room, with no changes in the overall trajectory participants would follow).

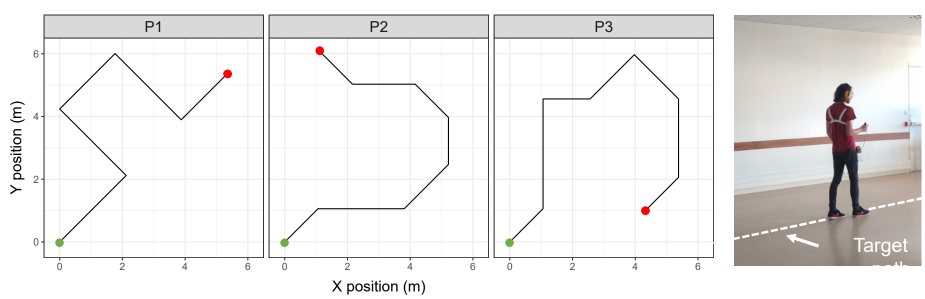

Fig. 5. Three paths `P1`, `P2`, and `P3` were used throughout the experiment. The starting point of each path is displayed in green and the end point in red (left). During trials, participants were guided along one of these paths without seeing it (right). The paths were regularly rotated by 180 degrees, so as to minimize learning effects without changing their shape.

4.2 Experimental Design

We evaluated the ability of the proposed haptic navigation strategies and rendering schemes to guide participants along target paths. We considered the following experimental variables:

- Navigation strategy: `A`, `R`, and `LA`, as presented in Sec. 3 and Fig. 2;
- Rendering scheme (information granularity): `4Dir` and `8Dir`, as shown in Fig. 3;
- Target paths: `P1`, `P2`, `P3`, as shown in Fig. 5.

The experiment was made of three blocks, one for each navigation strategy. Within each block, the considered navigation strategy was used with both rendering schemes on the three paths, one after the other (i.e., 6 trials per block). Strategies and rendering schemes presentation order was counter-balanced across participants, while path order was randomized. The starting point changed every three trials, i.e., when the rendering scheme changed.

At the beginning of each block, participants received explanations on the navigation strategy that would be used in the block. They were asked, for each trial, to follow the handle instructions to the best of their ability. Trials started with participants standing at the starting point and facing toward the opposite corner of the room. Trial stopped when reaching the end of the path (0.5 m or less from the end point) or after four minutes, whichever came first.

4.3 Collected Data

We collected position and orientation of the participant, duration of the trial, and information displayed by the handle. After each trial, participants were asked to evaluate their perceived success on a scale from 1 to 7. Participants also judged each rendering scheme, rating three statements on a 7-item Likert scale (1=Totally disagree, 7=Totally agree): Vibration were tiring (*Tiring*); Vibrations were easy to locate (*Locate*); Vibrations were difficult to interpret (*VibInterpret*). Participants also rated each navigation strategy through ten statements: I navigated confidently (*NavConfidence*); The navigation strategy was easy to use (*Use*); The guidance instructions were hard to interpret (*NavInterpret*); I could use it without preliminary instructions (*Instructions*); I learned to use it quickly (*LearnSpeed*); It is easy to learn to use it (*Learn*); It is fun to use (*Fun*); It is pleasant to use (*Pleasant*); The task is mentally demanding (*MantalDemand*); The task is physically demanding (*PhysicalDemand*). We also collected open comments throughout the experiment. At the end, participants were asked for their preferred strategy.

4.4 Results

We considered successful trials as trials where (i) participants reached the end of the path (i.e., 0.5 m or less from the end point) in less than four minutes and

(ii) they did not walk from one section of the path to another, i.e., did not "cut" the path. Participants were successful in 90% of trials (see Table 1 for results per strategy and rendering scheme; see Fig. 6 for trajectories representative examples). We used a Generalised Linear Mixed Model to analyze the participants success. Navigation strategy, rendering scheme, and path were considered as the independent variables, while participants as a random effect. We observed a significant effect of the navigation strategy only ($\chi^2(2, N{=}324) = 15.01$, $p<0.001$). Post-hoc analysis using Tukey's test highlighted a greater success for A vs. R ($Z{=}2.74$, $p<0.05$) and A vs. LA ($Z{=}3.61$, $p<0.01$).

Table 1. Mean success rates for each combination of strategy and rendering scheme.

	Attractive	Repulsive	Latent Attractive
4Dir	100%	93%	83%
8Dir	98%	87%	80%

For the rest of this section, we only take into account successful trials. Path efficiency ratio, measured as the ratio between the distance walked by participants and the length of the path, is minimal for A (Mean=1.35, SD=0.33), and greater for LA (Mean=2.87, SD=1.77) than for R (Mean=2.32, SD=1.09). Wilcoxon signed-rank test show a significant difference between all pairs of navigation strategies ($p<0.01$). While this difference is significant, it must be taken into account that the R and LA strategies provided feedback only when deviating more than 0.3 m from the path, so a higher error is expected. This effect can be observed when looking at the user's distance the path, which is lower for A than for the other strategies (A: mean=0.27, median=0.19; R: mean=0.35, median=0.31; LA: mean=0.36, median=0.31).

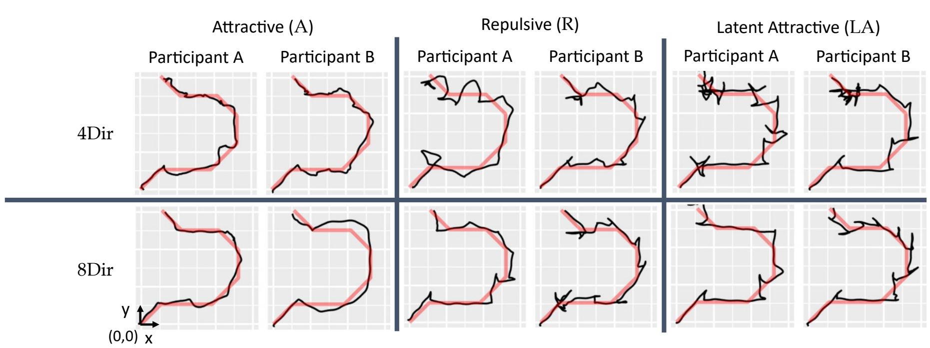

Fig. 6. Examples of trajectories of two participants on P2 (red: target path, black: participant trajectory). Trajectories tend to be smoother with the A strategy.

We also analyze the self-evaluated success from participants using a Cumulative link mixed-effects model. Results show a significant effect of the navigation strategy (χ^2(2, N=291) = 10.06, p<0.01) and path (χ^2(2, N=291) = 7.15, p<0.05). As expected, post-hoc Tukey's test showed higher evaluated success for `A` vs. `R` (Z=2.38, p<0.05) and `A` vs. `LA` (Z=2.95, p<0.01). `P1` also showed significantly better results than `P2` (p<0.05) for this metrics.

Regarding the subjective questionnaire (see Sec. 4.3), Wilcoxon signed-rank tests showed significant differences for *Use* between `A` and `LA` (mean: 5.5 vs. 4.0 , p<0.05), *Instructions* between `A` and `LA` (mean: 5.1 vs. 2.8 , p<0.01) and `A` and `R` (mean: 5.1 vs. 3.0 , p<0.01), *Learn* between `A` and `R` (mean: 5.9 vs. 4.6 , p<0.05), and for *Fun* between `A` and `LA` (mean: 6.0 vs. 4.6 , p<0.05). Significant differences were also observed for *VibInterpret* between `A` and `LA` (mean: 2.7 vs. 3.7 , p<0.01) and `A` and `R` (mean: 2.7 vs. 3.8 , p<0.01), as well as for *VibLocate* between `4Dir` and `8Dir` (mean: 5.8 vs. 5.1 , p<0.01). Other questions did not show significant differences. Corresponding boxplots are shown in Fig. 7. At the end of the experiment, 11 out of 18 participants chose `A` as their preferred strategy, 3 chose `R`, and 4 chose `LA`.

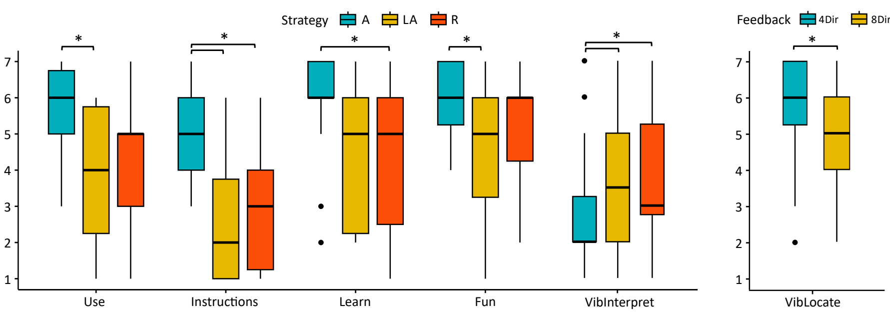

Fig. 7. Participants answers to items of the questionnaire over 7-item Likert scales.

5 Discussion

Our experiment evaluated the effectiveness of the proposed haptic navigation strategies and rendering schemes in guiding participants along target paths. Results showed that users were able to follow the proposed guidance successfully most of the time. Participants were able to use all three strategies successfully and quickly adapted to their use, confirming the intuitive nature of multi-actuator feedback in such a scenario. Overall, results show an advantage of `A`: trajectories carried out when being provided with this navigation strategy are smoother than the others (see, e.g., Fig. 6) and participants walked lower distances overall. This result is probably linked to the fact that the A strategy (i) is always active, continuously providing information, and that (ii) it conveys an intuitive information, i.e., the direction to go, similarly to turn-by-turn GPS systems.

However, the other navigation strategies still showed promising results. Indeed, several participants reported that evaluating their success in the attractive strategy A was harder, as they did not know how far they were from the target path (this strategy continuously provide feedback). These comments suggest that a promising approach could be to devise an adaptive navigation strategy, providing either information about the direction to follow or the deviation from the path, according to the user's performance or position: the A strategy could be used when users are close to the path, while LA or R could be used when deviation is too large.

After A, the R strategy seems to perform (slightly) better than LA. Comments from participants suggest that the information R provides is intuitive: vibrations can be interpreted as obstacles on which the user "bounces" and changes direction towards the correct path. Indeed, many participants described their experience with R and LA as "bumping into virtual walls", and compared the use of A to that of "a compass", which we found interesting. These two interpretations of the navigation strategies can be observed on the recorded trajectories. We highlight examples of these behaviors in Fig. 8. In failed trials, participants sometimes walked in the reverse direction of the path, which could be prevented by modifying the navigation strategy. In cases where users 'bounced' around the path (e.g., with R), some tended to turn around too much, thus walking from one side of the path to the other without making progress.

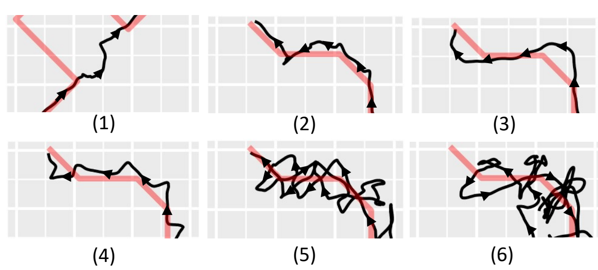

Fig. 8. Representative examples of participants behavior during navigation (red: target path, black: participant trajectory, arrows indicate the direction of motion). (1) Cut (unsuccessful trial): the participant goes too far from the path, directly reaching the other end and failing the trial; (2) Compass: a behavior often observed in the A strategy, the participant reorients at regular intervals using the handle as a compass; (3) Overshoot: the participant goes too far at turns, a result of either a fast walking speed or a long response time to navigation instructions; (4-5) Bouncing: a behavior often observed in the R and LA strategies, were participants tend to bounce from one side of the path to the other; (6) Never reaching the end (unsuccessful trial): the participant turned around before reaching the end of the path.

There does not seem to be a clear preference between `4Dir` and `8Dir`, with some participants finding the perception of `8Dir` difficult and other finding it intuitive and richer. If interpreted correctly, `8Dir` provides richer feedback, which allows users to change their trajectory more smoothly, as can be observed on Fig. 6. This result validates the use of both stimuli granularity for navigation, according to user's preference and expertise. Indeed, the personalization of the rendering stimuli is a challenging area of research that is promising in haptics [27].

Having vibrations displayed once every second for `A` was considered too much for some participants, while others found this frequency appropriate. Continuous vibration used in `R` and `LA` also received mixed feelings, showing again the importance of customization of the stimulation. The same applies for the intensity of the vibration, that some participants found appropriate and others too strong. Given the task and path chosen for the experiment, the frequency at which successive indications are provided seems appropriate: a longer delay between stimulation would have taken participants farther from the target path before the next instruction. A promising strategy in this respect is to consider a predictive guidance strategy, in which the instruction frequency depends on the (local) path complexity and speed of the user.

Finally, most participants reported that they enjoyed using the handle during the navigation task, with some of them finding `R` or `LA` strategies more "game-like", as if they were exploring a maze.

6 Conclusion

This paper introduces three navigation strategies for a multi-actuator haptic handle, considering two rendering schemes. We conducted a user study enrolling 18 participants. Results showed the ability of the proposed techniques to provide effective navigation instructions within our haptic handle. All navigation strategies were able to effectively guide participants along the target path. However, the "Attractive" strategy performed the best in terms of self-evaluated success, path efficiency ratio, and ease of learning.

Future work could improve the current navigation strategies by recalculating the path dynamically based on the user position (like in cars turn-by-turn navigation systems), considering the personalization and customization of the haptic stimuli, and combining instructions about the direction of the path with warnings about large deviations (e.g., combining the Attractive and Repulsive strategies presented here). The frequency of navigation instructions could also be improved, by adapting it depending on the local path shape and user movements. Although this study was carried out with able-bodied pedestrians, future work will focus on extending our haptic handle and navigation strategies to work with mobility assistance device, and testing with patients showing mobility and/or cognitive impairments.

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Disclosure of Interests. The authors have no competing interests to declare.

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